Optimality of linear optical Bell measurements. How much can ancillae help?

Andrea Olivo, Frédéric Grosshans

Optimality of linear optical Bell measurements

How much can ancillæ help?

Andrea Olivo[1,2], Frédéric Grosshans[1]

[1]INRIA Paris
[2]Laboratoire Aimé Cotton, Université Paris-Saclay

arXiv:1806.01243, Phys. Rev. A **98**, 042323

The task: unambiguous Bell measurement

$$|\phi^+\rangle = \frac{1}{\sqrt{2}}\big(\,|00\rangle + |11\rangle\,\big) \qquad |\psi^+\rangle = \frac{1}{\sqrt{2}}\big(\,|01\rangle + |10\rangle\,\big)$$
$$|\phi^-\rangle = \frac{1}{\sqrt{2}}\big(\,|00\rangle - |11\rangle\,\big) \qquad |\psi^-\rangle = \frac{1}{\sqrt{2}}\big(\,|01\rangle - |10\rangle\,\big)$$

Bell Measurement

Projective measurement on the Bell basis

Unambiguous

Outcome never wrong, but can fail with probability $\mathcal{P}_{\text{fail}}$

The task: unambiguous Bell measurement

$$|\phi^+\rangle = \frac{1}{\sqrt{2}}\big(\,|00\rangle + |11\rangle\,\big) \qquad |\psi^+\rangle = \frac{1}{\sqrt{2}}\big(\,|01\rangle + |10\rangle\,\big)$$

$$|\phi^-\rangle = \frac{1}{\sqrt{2}}\big(\,|00\rangle - |11\rangle\,\big) \qquad |\psi^-\rangle = \frac{1}{\sqrt{2}}\big(\,|01\rangle - |10\rangle\,\big)$$

Bell Measurement

Projective measurement on the Bell basis

Unambiguous

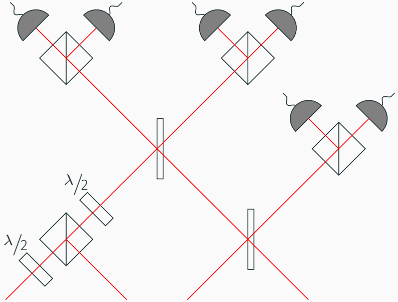
Outcome never wrong, but can fail with probability $\mathcal{P}_{\text{fail}}$

Quantum teleportation, dense coding, entanglement swapping...

The framework: static linear optics

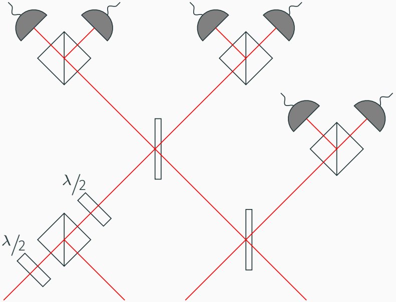
Why? Because...

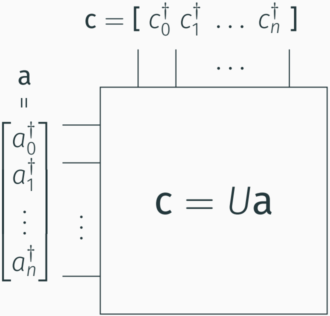
- ...experimentally easier: no feedforward



Why? Because...

- ...experimentally easier: no feedforward
- ...simple mathematical framework to work with

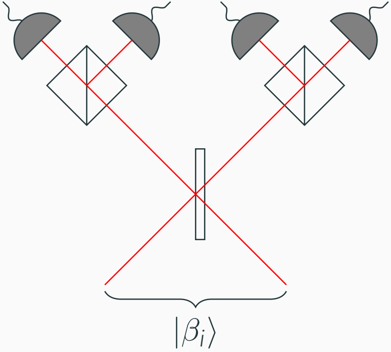




State of the art: Bell measurement without ancilla

[Braunstein and Mann, 1995]

- Known $\mathcal{P}_{\text{succ}} = \frac{1}{2}$ scheme [Braunstein & Mann, 1995]
- Optimal, even with feedforward [Calsamiglia & Lütkenhaus, 2001]



$$|\psi^+\rangle \longrightarrow \frac{1}{\sqrt{2}}(|1100\rangle + |0011\rangle)$$

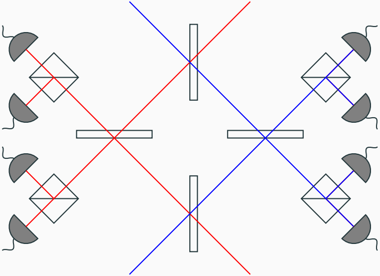
$$|\psi^-\rangle \longrightarrow \frac{1}{\sqrt{2}}(|1001\rangle - |0110\rangle)$$

$$|\phi^\pm\rangle \longrightarrow \frac{i}{2}(|2000\rangle \pm |0200\rangle + |0020\rangle \pm |0002\rangle)$$

Beyond 1/2

[Grice, 2011]

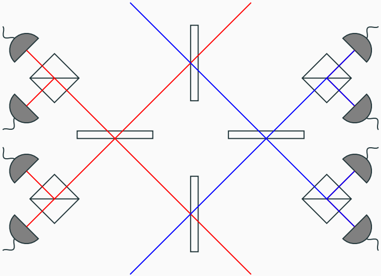
- $\mathcal{P}_{\text{succ}} = \frac{3}{4}$ with an extra $|\phi^+\rangle$ as ancilla
- $\mathcal{P}_{\text{fail}} = 2^{-N}$ with GHZ-like states of $2^N - 2$ photons



Beyond 1/2

[Grice, 2011]

- $\mathcal{P}_{\text{succ}} = \frac{3}{4}$ with an extra $|\phi^+\rangle$ as ancilla
- $\mathcal{P}_{\text{fail}} = 2^{-N}$ with GHZ-like states of $2^N - 2$ photons



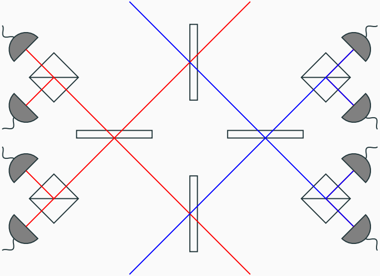
[Ewert and van Loock, 2014]

- $\mathcal{P}_{\text{succ}} = \frac{3}{4}$ with 4 single photons
- $\mathcal{P}_{\text{succ}} = \frac{25}{32}$ with 12 single photons
- Cons: limited efficiency
  Pros: unentangled ancilla
  (for the two above)

Beyond 1/2

[Grice, 2011]

- $\mathcal{P}_{\text{succ}} = \frac{3}{4}$ with an extra $|\phi^+\rangle$ as ancilla
- $\mathcal{P}_{\text{fail}} = 2^{-N}$ with GHZ-like states of $2^N - 2$ photons



[Ewert and van Loock, 2014]

- $\mathcal{P}_{\text{succ}} = \frac{3}{4}$ with 4 single photons
- $\mathcal{P}_{\text{succ}} = \frac{25}{32}$ with 12 single photons
- Cons: limited efficiency
  Pros: unentangled ancilla
  (for the two above)

What can we say about their optimality?

Our work

Ideally, we want an upper bound on $\mathcal{P}_{\text{succ}}$ depending on the ancilla.

We provide:

Our work

Ideally, we want an upper bound on $\mathcal{P}_{\text{succ}}$ depending on the ancilla.

We provide:

- An analytical bound for polarization-preserving interferometers

Our work

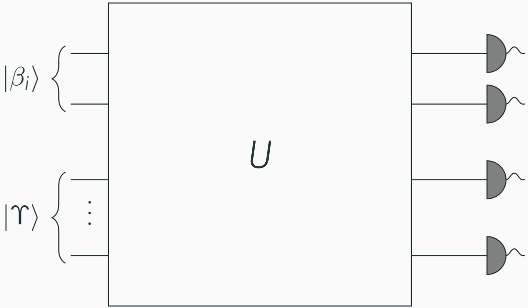
Ideally, we want an upper bound on $\mathcal{P}_{\text{succ}}$ depending on the ancilla.

We provide:

- An analytical bound for polarization-preserving interferometers
- A thorough numerical search for generic (small) interferometers

Analytical upper bound

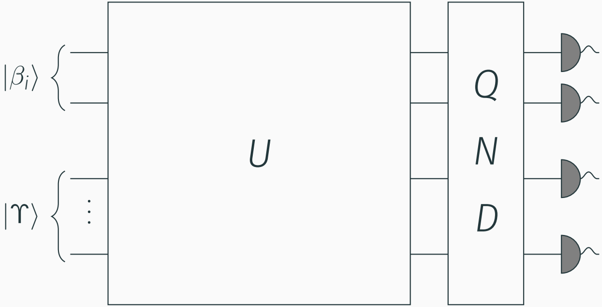
Overview of the proof



Input: $|\Psi_{\text{in}}\rangle = |\beta_i\rangle\,|\Upsilon\rangle$, with $|\Upsilon\rangle = \sum_{\lambda=0}^{k} v_\lambda\,|\Upsilon,\lambda\rangle$ a k-photon ancilla

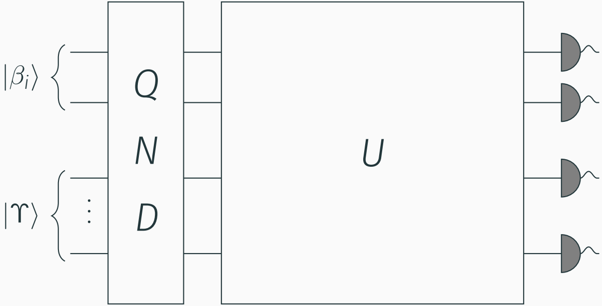
Each $|\Upsilon,\lambda\rangle$ is a state with λ horizontally polarized photons

Overview of the proof



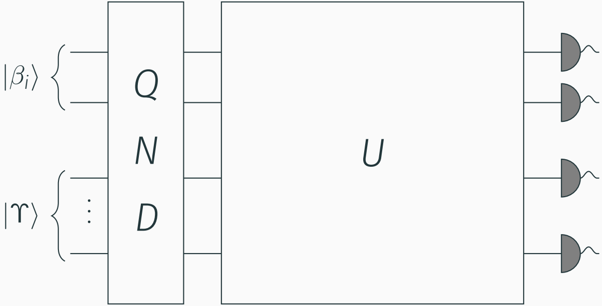
Output statistics unchanged under a projective measurement of the horizontally-polarized photon number of $|\Psi_{\mathrm{out}}\rangle$

Overview of the proof



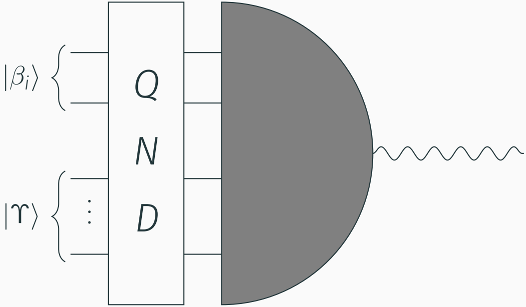
Measurement commutes $\Longleftrightarrow$ polarization-preserving network

Overview of the proof



$|\psi^+\rangle$, $|\psi^-\rangle$ and $|\phi^\pm\rangle$ are mapped in three orthogonal subspaces $\forall\lambda$

Overview of the proof



Non-orthogonal post-measurement states $|\Lambda^{\pm}\rangle$ corresponding to $|\phi^{+}\rangle$ and $|\phi^{-}\rangle$ can be discriminated with optimal $\mathcal{P}_{\text{succ}} \leq 1 - |\langle\Lambda^{+}|\Lambda^{-}\rangle|$.

Upper bounds

Ancilla polarization-based upper bound:

$$\mathcal{P}_{\text{fail}} \geq \frac{1}{2}\left(\max_{\lambda \text{ even}} |v_\lambda|^2 + \max_{\lambda \text{ odd}} |v_\lambda|^2 \right) \tag{1}$$

(looser) Photon number-based upper bound:

$$\mathcal{P}_{\text{fail}} \geq \frac{1}{\lceil k+1 \rceil_{\text{even}}} \tag{2}$$

N.B. The Grice's schemes saturate both bounds!

Linear network optimizer

Polynomial representation

Second quantization, n-modes interferometer.

Input/output state $\longrightarrow$ polynomial in the input/output mode operators:

$$|\psi_{\text{in}}\rangle = P_{\text{in}}(a_1^\dagger, \ldots, a_n^\dagger)\,|0\rangle \qquad |\psi_{\text{out}}\rangle = P_{\text{out}}(c_1^\dagger, \ldots, c_n^\dagger)\,|0\rangle$$

Action of the interferometer on $|\psi_{\text{in}}\rangle \longrightarrow$ unitary transformation U acting on the mode operators:

$$a_i^\dagger = \sum_{j=1}^{n} u_{ij}\, c_j^\dagger$$

Measurement of $|\psi_{\text{out}}\rangle$ by an array of PNRD.
Detection event $\longrightarrow$ a configuration of clicks at the output.

The method

Task: maximize $\mathcal{P}_{\text{succ}}$ over all possible n-modes interferometers, using k-photon ancilla $|\Upsilon\rangle$

The method

Task: maximize $\mathcal{P}_{\text{succ}}$ over all possible n-modes interferometers, using k-photon ancilla $|\Upsilon\rangle$

1. For each $|\psi_{\text{in}}\rangle = |\beta_i\rangle\,|\Upsilon\rangle \longrightarrow 2^{\text{nd}}$ quantization output polynomial

The method

Task: maximize $\mathcal{P}_{\text{succ}}$ over all possible n-modes interferometers, using k-photon ancilla $|\Upsilon\rangle$

1. For each $|\psi_{\text{in}}\rangle = |\beta_i\rangle\,|\Upsilon\rangle \longrightarrow 2^{\text{nd}}$ quantization output polynomial
2. Functions $p_i^e(U) \longrightarrow$ probability of detection event e for input β_i

The method

Task: maximize $\mathcal{P}_{\mathrm{succ}}$ over all possible n-modes interferometers, using k-photon ancilla $|\Upsilon\rangle$

1. For each $|\psi_{\mathrm{in}}\rangle = |\beta_i\rangle\,|\Upsilon\rangle \longrightarrow 2^{\mathrm{nd}}$ quantization output polynomial
2. Functions $p_i^e(U) \longrightarrow$ probability of detection event e for input β_i

Above steps are automatic symbolic computation. Then:

The method

Task: maximize $\mathcal{P}_{\text{succ}}$ over all possible n-modes interferometers, using k-photon ancilla $|\Upsilon\rangle$

1. For each $|\psi_{\text{in}}\rangle = |\beta_i\rangle\,|\Upsilon\rangle \longrightarrow 2^{\text{nd}}$ quantization output polynomial
2. Functions $p_i^e(U) \longrightarrow$ probability of detection event e for input β_i

Above steps are automatic symbolic computation. Then:

3. Functions $p_i^e(U)$ are hardcoded in C

The method

Task: maximize $\mathcal{P}_{\text{succ}}$ over all possible n-modes interferometers, using k-photon ancilla $|\Upsilon\rangle$

1. For each $|\psi_{\text{in}}\rangle = |\beta_i\rangle\,|\Upsilon\rangle \longrightarrow 2^{\text{nd}}$ quantization output polynomial
2. Functions $p_i^e(U) \longrightarrow$ probability of detection event e for input β_i

Above steps are automatic symbolic computation. Then:

3. Functions $p_i^e(U)$ are hardcoded in C
4. A f.o.m. $f(U)$ is numerically optimized over $U(n)$

An example: no ancilla on $|\phi^+\rangle$

$$n = 4,\ k = 0 \qquad P_{\text{in}} = \frac{1}{\sqrt{2}}(a_1^\dagger a_3^\dagger + a_2^\dagger a_4^\dagger)$$

An example: no ancilla on $|\phi^+\rangle$

$$n = 4,\, k = 0 \qquad P_{\text{in}} = \tfrac{1}{\sqrt{2}}(a_1^\dagger a_3^\dagger + a_2^\dagger a_4^\dagger)$$

$$\downarrow$$

$$P_{\text{out}} = \frac{1}{\sqrt{2}}\Big(\sum_{j_1} u_{1j_1} c_{j_1}^\dagger\Big)\Big(\sum_{j_2} u_{3j_2} c_{j_2}^\dagger\Big) + \frac{1}{\sqrt{2}}\Big(\sum_{j_3} u_{2j_3} c_{j_3}^\dagger\Big)\Big(\sum_{j_4} u_{4j_4} c_{j_4}^\dagger\Big)$$

An example: no ancilla on $|\phi^+\rangle$

$$n = 4,\ k = 0 \qquad P_{\text{in}} = \tfrac{1}{\sqrt{2}}(a_1^\dagger a_3^\dagger + a_2^\dagger a_4^\dagger)$$

$$\downarrow$$

$$P_{\text{out}} = \frac{1}{\sqrt{2}}\Big(\sum_{j_1} u_{1j_1} c_{j_1}^\dagger\Big)\Big(\sum_{j_2} u_{3j_2} c_{j_2}^\dagger\Big) + \frac{1}{\sqrt{2}}\Big(\sum_{j_3} u_{2j_3} c_{j_3}^\dagger\Big)\Big(\sum_{j_4} u_{4j_4} c_{j_4}^\dagger\Big)$$

$$\downarrow$$

2000	$u_{11}u_{31} + u_{21}u_{41}$
0200	$u_{12}u_{32} + u_{22}u_{42}$
0020	$u_{13}u_{33} + u_{23}u_{43}$
0002	$u_{14}u_{34} + u_{24}u_{44}$
1100	$(u_{11}u_{32} + u_{12}u_{31} + u_{21}u_{42} + u_{22}u_{41})/\sqrt{2}$
1010	$(u_{11}u_{33} + u_{13}u_{31} + u_{21}u_{43} + u_{23}u_{41})/\sqrt{2}$
1001	$(u_{11}u_{34} + u_{14}u_{31} + u_{21}u_{44} + u_{24}u_{41})/\sqrt{2}$
0110	$(u_{12}u_{33} + u_{13}u_{32} + u_{22}u_{43} + u_{23}u_{42})/\sqrt{2}$
0101	$(u_{12}u_{34} + u_{14}u_{32} + u_{22}u_{44} + u_{24}u_{42})/\sqrt{2}$
0011	$(u_{13}u_{34} + u_{14}u_{33} + u_{23}u_{44} + u_{24}u_{43})/\sqrt{2}$

An example: no ancilla on $|\phi^+\rangle$

$$n = 4,\ k = 0 \qquad P_{\text{in}} = \tfrac{1}{\sqrt{2}}(a_1^\dagger a_3^\dagger + a_2^\dagger a_4^\dagger)$$

$$\downarrow$$

$$P_{\text{out}} = \frac{1}{\sqrt{2}}\Big(\sum_{j_1} u_{1j_1} c_{j_1}^\dagger\Big)\Big(\sum_{j_2} u_{3j_2} c_{j_2}^\dagger\Big) + \frac{1}{\sqrt{2}}\Big(\sum_{j_3} u_{2j_3} c_{j_3}^\dagger\Big)\Big(\sum_{j_4} u_{4j_4} c_{j_4}^\dagger\Big)$$

$$\downarrow$$

2000	$u_{11}u_{31} + u_{21}u_{41}$
0200	$u_{12}u_{32} + u_{22}u_{42}$
0020	$u_{13}u_{33} + u_{23}u_{43}$
0002	$u_{14}u_{34} + u_{24}u_{44}$
1100	$(u_{11}u_{32} + u_{12}u_{31} + u_{21}u_{42} + u_{22}u_{41})/\sqrt{2}$
1010	$(u_{11}u_{33} + u_{13}u_{31} + u_{21}u_{43} + u_{23}u_{41})/\sqrt{2}$
1001	$(u_{11}u_{34} + u_{14}u_{31} + u_{21}u_{44} + u_{24}u_{41})/\sqrt{2}$
0110	$(u_{12}u_{33} + u_{13}u_{32} + u_{22}u_{43} + u_{23}u_{42})/\sqrt{2}$
0101	$(u_{12}u_{34} + u_{14}u_{32} + u_{22}u_{44} + u_{24}u_{42})/\sqrt{2}$
0011	$(u_{13}u_{34} + u_{14}u_{33} + u_{23}u_{44} + u_{24}u_{43})/\sqrt{2}$

Optimization: a case for symbolic computation

Why not using pen and paper for $p_i^e(U)$?

For (small!) $\frac{3}{4}$ Grice's scheme:

Total number of functions	1320
Independent	just 5

Optimization: a case for symbolic computation

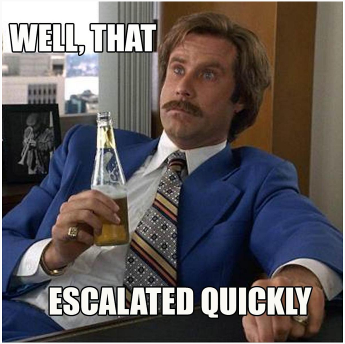
Why not using pen and paper for $p_i^e(U)$?

For (small!) $\frac{3}{4}$ Grice's scheme:

Total number of functions	1320
Independent	just 5

But 2^{nd} iteration, $\frac{7}{8}$:

Total number of functions	490314
Independent	22
Total number of terms	$1{,}8 \cdot 10^6$



Results

Ancilla: a single photon

Simplest type of ancilla, no known scheme

- Polarization-preserving bound predicts $\mathcal{P}_{\text{succ}} \leq \frac{1}{2}$
- Numerical search confirms the result

Ancilla: a single photon

Simplest type of ancilla, no known scheme

- Polarization-preserving bound predicts $\mathcal{P}_{\text{succ}} \leq \frac{1}{2}$
- Numerical search confirms the result

We find no advantage using just one extra photon.

More single, unentangled photons

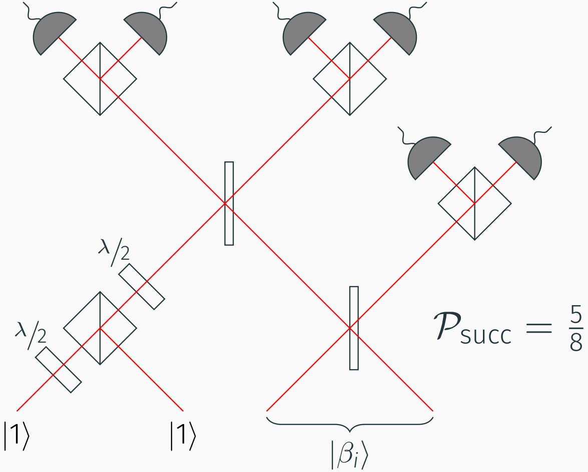
k photons	Pol. Pres. bound	Num. search	Explicit scheme
2	5/8	5/8	5/8
4	3/4	3/4	3/4
6	13/16	3/4	—
8	25/32	—	49/64
12	13/16	—	25/32

More single, unentangled photons

k photons	Pol. Pres. bound	Num. search	Explicit scheme
2	5/8	5/8	5/8
4	3/4	3/4	3/4
6	13/16	3/4	—
8	25/32	—	49/64
12	13/16	—	25/32

just 2 single photons beat 50% limit!

The “half”-Ewert & van Loock scheme



Also independently found by Ewert & van Loock

Entangled ancillæ

Do entangled ancillæ help?

- Grice's one-Bell-pair: optimal $\frac{3}{4}$, by numerical search

Entangled ancillæ

Do entangled ancillæ help?

- Grice's one-Bell-pair: optimal $\frac{3}{4}$, by numerical search
- 2 Bell pairs: no better than one Bell pair
- 3 to N Bell pairs: out of reach with 12 cores, 256GB RAM cluster
    - Pol. pres. bound predicts $\mathcal{P}_{\text{fail}} \gtrsim \frac{1}{\sqrt{\pi k}} > \frac{1}{k}$

Entangled ancillæ

Do entangled ancillæ help?

- Grice's one-Bell-pair: optimal $\frac{3}{4}$, by numerical search
- 2 Bell pairs: no better than one Bell pair
- 3 to N Bell pairs: out of reach with 12 cores, 256GB RAM cluster
  - Pol. pres. bound predicts $\mathcal{P}_{\text{fail}} \gtrsim \frac{1}{\sqrt{\pi k}} > \frac{1}{k}$
- Grice's $\frac{7}{8}$ scheme needs $n = 16, k = 6$: barely out of reach

Conclusion

Achievements

What can we say on the optimal $\mathcal{P}_{\text{succ}}$ of unambiguous Bell measurement?

- Upper bound for polarization-preserving interferometers, saturated by known schemes
- Hybrid numerical/symbolical search
  - Confirms optimality of (some) known schemes
  - New 2-photon scheme with $\mathcal{P}_{\text{succ}} = \frac{5}{8}$
- Explored several ancillæ$\longrightarrow\frac{3}{4}$ stays the best (for small networks)

Open questions

We have automated second quantization simulator, up to 10 modes and 8 photons.

Open questions

We have automated second quantization simulator, up to 10 modes and 8 photons.

- Include noise. But how to generalize "unambiguous"?
- Adapt for state generation problem

Thank you